REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (*DD-MM-YYYY*)	2. REPORT TYPE	3. DATES COVERED (*From - To*)
AUG 2011	**Conference Paper (Post Print)**	JUL 2010 – JUL 2010

4. TITLE AND SUBTITLE
SITE DIVERSITY CONSIDERATIONS FOR V/W BAND SATELLITE

5a. CONTRACT NUMBER
IN-HOUSE

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62702F

6. AUTHOR(S)
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5d. PROJECT NUMBER
RIGD

5e. TASK NUMBER
IH

5f. WORK UNIT NUMBER
CM

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFRL/RIGD
525 Brooks Road
Rome NY 13441-4505

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/RIGD
525 Brooks Road
Rome NY 13441-4505

10. SPONSOR/MONITOR'S ACRONYM(S)
N/A

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-RI-RS-TP-2011-32

12. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED. PA #: 88ABW-2010-3874
DATE CLEARED: 19 JUL 2010

13. SUPPLEMENTARY NOTES
Published in Proceedings. Ka and Broadband Conference, 2010, Milan Italy, October 2010. This is a work of the United States Government and is not subject to copyright protection in the United States.

14. ABSTRACT
This paper examines the potential of using site diversity to mitigate fade associated with V/W band satellite communications. Site diversity based on a log-normal distribution for rain attenuation is applied. Limitations due to cloud attenuation are considered. The site diversity methodology is extended to include cloud attenuation.

15. SUBJECT TERMS
V/W Band Satellite Communications, Attenuation Models

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	19b. TELEPHONE NUMBER (*Include area code*)
U	U	U	UU	9	THOMAS SCATKO	N/A

SITE DIVERSITY CONSIDERATIONS FOR V/W BAND SATELLITE COMMUNICATIONS

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Abstract

This paper examines the potential of using site diversity to mitigate fade associated with V/W band satellite communications. Site diversity based on a log-normal distribution for rain attenuation is applied. Limitations due to cloud attenuation are considered. The site diversity methodology is extended to include cloud attenuation.

1. Introduction

The V/W satellite communication bands of 81-86 GHz uplink and 71-76 GHz down link are attractive due to the available spectrum and high data rate potential. On the other hand, atmospheric attenuation will limit the availability. We envision that a future V/W system design will employ the use of high gain antennas and central ground stations. Still, link margins will be quite limited and fade mitigation techniques will be needed. As part of our concept study, we examine the use of site diversity to improve availability, which is our metric of interest.

A V/W band system operating at full or near full bandwidth will likely be limited to rain rates of less than only a few mm/hr due to the high specific attenuation at these frequencies. Thus we need a site diversity methodology that is appropriate for stratiform type rains. Empirical based site diversity models based on measurements associated with convective type rain are not applicable to V/W considerations. Instead we use a statistical based model approach to calculate the joint probability of attenuation.[1,2] Although rain is the dominant source of attenuation, cloud attenuation at V/W frequencies can also be significant and could potentially limit the usefulness of site diversity. We extend the rain site diversity analysis to include clouds. We consider two cases of cloud attenuation; cloud attenuation fully correlated with rain, and cloud attenuation independent of rain.

We consider in this paper two ground sites within a single beam. Since the spatial correlation of rain rate may extend to 1000 km[1], the use of a narrow beam means that the attenuations at the two sites are likely not statistically independent. Therefore we also consider the antenna gain pattern and the decrease in link margin with increase in site separation. This is of course a function of the satellite location and the orientation of the ground sites. In our analysis we assume a 1 m diameter antenna for the space segment pointed at midpoint between the ground stations, with a separation orientation that is perpendicular to the earth-space path. Our objective is not to produce specific predictions, but rather to examine the issues and applicability of site diversity to V/W band. We consider here the problem of site diversity for Rome NY, which is in a Crane D2 rain climate zone (old ITU K). We use a frequency of 80 GHz as a surrogate for the V/W bands in our analysis. The single site attenuation predictions for an elevation angle of 30° are shown in Figure 1. The single site rain attenuation predictions are based on a modified version of Crane's two-component model[3] in which the rain rate statistics are modeled as an exponential component (volume cells) and a log-normal component

(debris). The parameters for the exponential and log-normal rain rate distributions are taken from Crane [4]. Crane's model assumes different rain heights for convective (cell) and stratiform (debris) rain, but does not account for the melting layer attenuation. We add a melting layer by increasing the debris rain height by the effective height $H_{BB}(f)$ given by Capsoni *et. al.* [5] We differ with Crane in the algorithm used to calculate the rain attenuation. The attenuation due to the volume cells is calculated using a uniform cell model in a manner similar to that used by Misme and Waldteufel[6]. For the debris component we adopt the statistical approach of Lin [7]. For the V/W band calculations the log-normal component dominates at the attenuation levels of interest, and the output of the model turns out to be the input to the site diversity model. The attenuation due to clouds, gases, and scintillation are calculated according to the ITU recommendations.[2] The attenuations are combined on an equiprobability basis:

$$A_T(p) = A_R(p) + A_C(p) + A_G(p) + A_S(p)\ . \tag{1}$$

While this likely overestimates the total attenuation exceedance it allows consistency when separating out the attenuation effects.

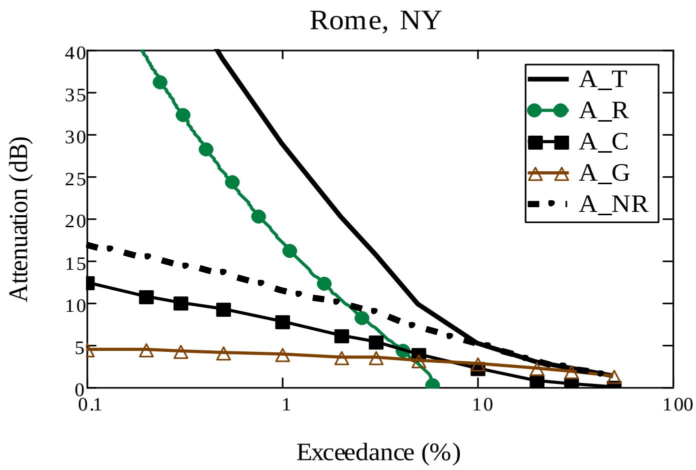

Figure 1. Attenuation predictions for Rome, NY.

2. Rain site-diversity

We begin with a site diversity model based on that derived by Paraboni and Barbaliscia[1] and recommended by the ITU[2]. This method assumes a conditioned log-normal distribution for rain attenuation, given by

$$P(A > a) = P^A Q\left(\frac{lna - m_A}{\sigma_A}\right) \tag{2}$$

Where Q is the complementary cumulative normal distribution, P^A is the probability of attenuation on the earth-space path, m_A and σ_A are the log-normal statistical parameters. In this method, the joint probability (%) that the attenuation on path *1* is greater than a_1 and the attenuation on path *2* is greater than a_2 is given by

$$P(A_1 > a_1, A_2 > a_2) = 100x\ (P_r\ x\ P_a\ ), \tag{3}$$

where

$$P_r = \frac{1}{2\pi\sqrt{1-\rho_r^2}} \int_{R_1}\int_{R_2} exp\left[-\left(\frac{r_1^2-2\rho_r r_1 r_2+r_2^2}{2(1-\rho_r^2)}\right)\right] dr_1 dr_2 \tag{4}$$

and

$$P_a = \frac{1}{2\pi\sqrt{1-\rho_a^2}} \int_{Z_1}\int_{Z_2} exp\left[-\left(\frac{a_1^2-2\rho_a a_1 a_2+a_2^2}{2(1-\rho_a^2)}\right)\right] da_1 da_2 \tag{5}$$

are the bivariate normal distributions. The lower limits of integration are determined by the log-normal statistical parameters. Paraboni and Barbaliscia[1] relate P_r to the probability that it is raining at both sites, and the thresholds R_k are given by

$$R_k = Q^{-1}\left(\frac{P_k^{rain}}{100}\right) \tag{6}$$

where P_k^{rain} is the point probability of rain (%) and Q^{-1} is the inverse complementary cumulative normal distribution. We suggest that the appropriate threshold parameter in equation (6) should be P_k^A, which is the probability of attenuation due to rain determined by the rain attenuation prediction model and may be different than P_k^{rain}, as it is in our rain attenuation model. In this way equation (3) reduces to equation (2) in the limit of zero separation, as it must. The lower integration limit in equation (5) is given by the normalized log attenuation

$$Z_k = \frac{ln a_k - m_{A_k}}{\sigma_{A_k}} \ . \tag{7}$$

We still need the spatial correlation functions ρ_r and ρ_a. These are most likely geographic dependent. In the absence of locally determined values we use the model for ρ_r proposed by Paraboni and Baraliscia[1] based on measurements made in Italy.

$$\rho_r(d) = 0.7e^{-\left(\frac{d}{60}\right)} + 0.3e^{-\left(\frac{d}{700}\right)^2} , \tag{8}$$

where d is the site separation. As discussed below, we take the rain rate correlation as the best estimate of the rain attenuation correlation.

From Figure 1 it is seen that the non-rain contributions (A_{NR}) to the attenuation are significant at all probability levels of interest. In order to benefit from rain site diversity a significant link margin is necessary to overcome the non-rain effects. Since the rain attenuation increases at a greater rate with decreasing probability than the other attenuation effects and is the dominant source of attenuation at lower probabilities, it seems reasonable that the rain site diversity model can be used. Therefore, the values of A_i and a_i in equation (2) are with respect to the excess attenuations available for rain:

$$a_i = A_{T_i} - A_{GCS_i} \tag{9}$$

where A_{gcs} is the attenuation associated with gases, clouds, and scintillation, and A_{Ti} is determined by the available link margin, referenced to no atmospheric attenuation. Predictions are shown in Figure 2 for link margins of *12.5* and *15 dB*, with and without antenna pattern losses.

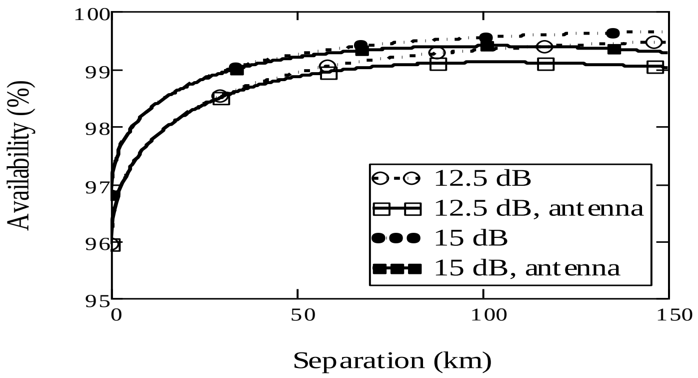

Figure 2. Rain model site-diversity availabilities at Rome, NY, f = 80 GHz

3. Combined rain and cloud site-diversity

The site diversity results using the rain site diversity model neglected additional effects due to non rain attenuation, particularly clouds, that might limit the availability for a site diversity scenario. Significant cloud attenuation at non-rainy times has been reported in the literature[8-11]. The upper level of availability may be limited by the non-rain attenuation, if the link margin is not great enough. However, we should expect site diversity will also help mitigate cloud attenuation. If the cloud attenuation is log-normal distributed, then we can apply the same methodology for cloud attenuation as was used for rain attenuation to estimate the attenuation mitigation. Our approach then is to fit the ITU cloud attenuation predictions to a log-normal distribution. We then need the spatial correlation functions for cloud cover and cloud attenuation. The analysis of Benarroch *et. al*[13] of the spatial cloud cover in Spain indicates that the spatial correlation properties of clouds may not be much different than that of rain. As a first order approximation we use the same correlation function for cloud site diversity that we used for rain.

Given the possible impact of cloud attenuation at V/W bands, we consider a site diversity model that combines the effects of rain and cloud attenuation. We consider the two cases of fully correlated and independent attenuation. Here we need the unconditioned probability density functions $f_R(A)$ and $f_C(A)$. It is convenient to model the rain and cloud attenuations as log-normal distributed. We obtain these by numerical regression of the rain attenuation prediction model and the ITU cloud attenuation model. The disadvantage of this approach is that the unconditioned distributions are not exactly log-normal so there is some loss in accuracy, and the distribution is valid only above a minimum value of attenuation. In our case, the log-normal fit is made to provide a reasonable approximation over the parameter space of interest. Next we need the single site distribution function for the combined cloud and rain attenuation, $f_{RC}(A)$. For the correlated case, we add the rain and cloud attenuations on an equiprobability basis, and fit the resulting distribution to a lognormal. For the independent case we convolve the rain and cloud probability densities. The results are shown in Figure 3.

There are two possibilities to calculate the combined site diversity probability for the correlated case. The first approach is to use the same procedure discussed above, but with the statistical parameters determined by the fit of a conditioned lognormal distribution to $A_{RC} = A_R+A_C$. The other approach is to use the unconditioned distribution, in which case the probability is given by

$$P(A_1 > a_1, A_2 > a_2) = 100x\ (P_a), \tag{10}$$

where P_a is the normal bivariate joint distribution as given by (5) and ρ_a is now the correlation function for the log attenuation of A_{RC}. We are of course assuming the spatial correlation function for rain and clouds have the same spatial dependence. The values for a_i again are with respect to the excess attenuation. These two approaches are equivalent, and give the same results within the limits of the fitting process, and provided that the correlation functions are the same, as discussed below.

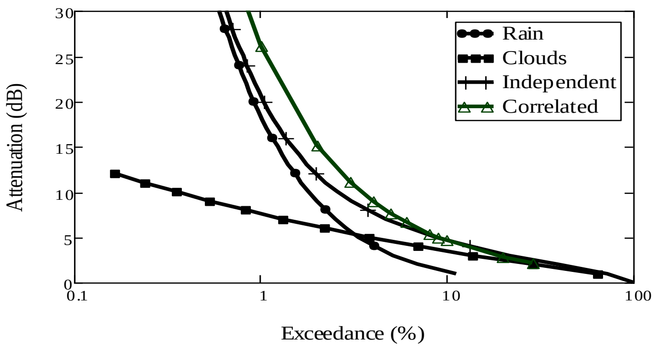

Figure 3. Rain, Clouds, and Rain+Clouds attenuation distributions.

For the independent case we need to use a different methodology to calculate the availability from site diversity. Here we use a Monte Carlo simulation of the site diversity. We generate an Nx2 matrix of attenuation corresponding to attenuation at the two sites from random number pairs generated from a correlated bivariate log-normal distribution

$$fj_{R,C}(A_1,A_2) = \frac{1}{2\pi A_1 A_2 \sigma_1 \sigma_2 \sqrt{1-\rho_a^2}} e^{-\left(\frac{1}{2(1-\rho_a^2)}\right)\left[\frac{(\ln(A_1)-m_1)^2}{\sigma_1^2}+\frac{(\ln(A_2)-m_2)^2}{\sigma_2^2}-2\rho_a\left(\frac{\ln(A_1)-m_1}{\sigma_1}\right)\left(\frac{\ln(A_2)-m_2}{\sigma_2}\right)\right]}, \quad (11)$$

where A_1 and A_2 are the attenuations at sites *1* and *2*, $m_{1,2}$ and $\sigma_{1,2}$ are the corresponding mean and standard deviations of the unconditioned lognormal distributions, and ρ_a is the spatial correlation coefficient for the attenuation. This is done for both the rain and cloud attenuation, and the attenuations are added to obtain A_{RC} at each site. The spatial correlation function does not have to be the same for both clouds and rain, although in our simulation it was. Results from the combined cloud and rain site diversity are shown in Figures 4 and 5 for link margins of 12.5 and 15 dB.

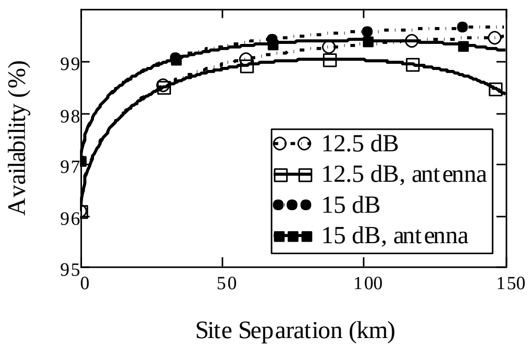

Figure 4. Site diversity availabilities for different link margins with correlated rain plus clouds.

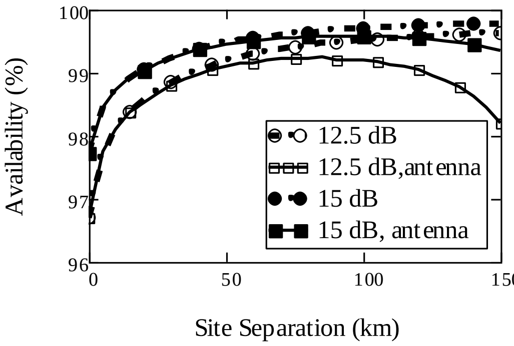

Figure 5. Site diversity availabilities for different link margins with independent rain and cloud. attenuation.

4. Discussion

Comparing Figures 2 and 4 it is seen that including cloud attenuation as a variable resulted in a slight reduction of availability. Treating cloud attenuation independent of rain attenuation increased the availability owing to the reduced total attenuation. The above results suggest that by using site diversity link availabilities of greater than 99% may be possible at V/W bands using modest link margins without compromising bandwidth, even in non optimal rain climates, such as Rome NY. In

comparison, single site link margins of 30 dB and 40 dB would be required for 99% and 99.5% availabilities, respectively. Site separation of over 50 km is needed. The optimum spacing depends on orientation with respect to the satellite as well as the available link margin. It also depends on the spatial correlation characteristics of the attenuation.

The spatial correlation function for rain and cloud attenuation is a key parameter in evaluating the utility of site diversity. We discuss first the rain attenuation correlation. We note that the ITU[2] recommendation for the spatial log rain attenuation ρ_a is given by

$$\rho_a(d) = 0.94e^{-\left(\frac{d}{30}\right)} + 0.06e^{-\left(\frac{d}{500}\right)^2} \quad , \tag{12}$$

which has a considerably shorter correlation length than the rain rate. In our analysis we have assumed that ρ_a is the same as the rain rate correlation ρ_r. This is based on the following considerations. Rain specific attenuation is related to rain rate by the power law relation

$$\gamma = aR^b \ . \tag{13}$$

Therefore we should expect specific attenuation to have a similar spatial characteristic as rain rate.[14] The long correlation length associated with stratiform rains means a small statistical variation over the 3-5 km path length associated with the attenuation. Monte Carlo simulations confirm that the correlation of the ln(attenuation) has a similar spatial dependence as that of the ln(rain rate). In fact, this approach allows the determination of ρ_a from ρ_r. Furthermore, the correlation characteristics of the rain diversity model given by equation (3) are determined primarily by ρ_r, and not ρ_a. Using equation (8) for ρ_a results in a small decrease in availability. However, in the unconditioned probability analysis where we use only the spatial correlation function of attenuation, the choice of that ρ_a can make a significant difference in prediction of availability. Equating the rain attenuation spatial correlation to rain rate correlation maintains consistency with the ITU recommendation for rain site diversity when using the unconditioned correlation distribution.

The spatial correlation function for rain rate also depends upon the type of rain,[15] the rain rate threshold[13], and the integration time.[16] Lin's[7] estimate of the rain attenuation correlation length of approximately 5 km was based on measurements at 18GHz, and therefore biased to the shorter correlation lengths of convective type rain. Morita and Higuti [14] found short spatial correlation lengths (~10km) from rain gauge data in Japan, but their analysis utilized high rain rate data. Since V/W systems will likely be limited to rain of only a few mm/hr rain rates, these short correlation lengths do not seem applicable here. Measurements of spatial rain rate correlation in Great Britain[17] based on rain gauge and radar data indicate correlation lengths less than 10 km, although the threshold levels were not given. Crane[15] gives a value of the ln(rain rate) correlation length of about 50 km for the debris rain component of his two-component rain model. The analysis of Benarroch *et al.*[13] of the spatial correlation of rain rate in Spain using low thresholds yielded similar correlation characteristics of long correlation lengths as that found by Parboni and Barbaliscia[1] in Italy. A comparison of some of the spatial correlation functions is shown in Fig. 6. Here *M-H* indicates the spatial correlation function of Morita and Higuti[14] and *F* is the spatial correlation function measured in Great Britain by Fukuchi[16] for 5 minute and 60 minute integration times. Figure 7 shows the effect of the rain spatial correlation characteristics on site diversity for *12.5 dB* link margin. Here we have used the rain site diversity model of section 2 and included the antenna pattern. It is evident that accurate knowledge of the correlation characteristics is needed provide a reliable assessment of site diversity. In the absence of specific locally measured data, we have adopted the use of the longer correlation lengths given by equation (8) for our analysis of the V/W band frequencies.

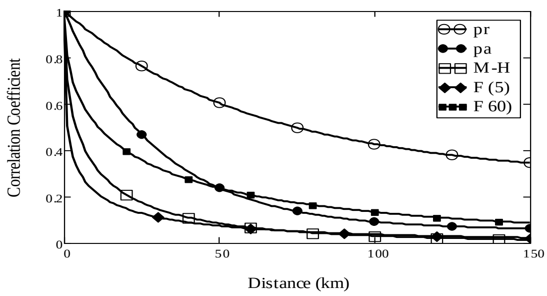

Figure 6. Comparison of different correlation functions.

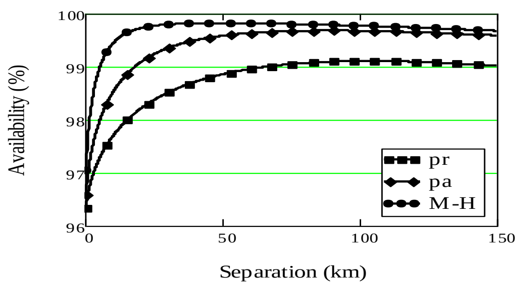

Figure 7. Site diversity availability from different correlation functions.

We also note that the relationship between the correlation coefficient of lognormal variates and the transformed normal variates is given by

$$\rho_n = \frac{ln\left[1+\rho_{ln}\sqrt{\left(e^{\sigma_1{}^2}-1\right)\left(e^{\sigma_2{}^2}-1\right)}\right]}{\sigma_1\sigma_2} \quad . \tag{14}$$

The spatial correlation properties of clouds are less well studied. Benarroch *et al.[15]* examined the spatial properties of cloud cover in Spain using synoptic data, but we are not aware of any quantitative measurements of the spatial correlation properties of cloud attenuation. While we might assume that in the correlated case the cloud attenuation correlation can be approximated by that of rain rate, the independent case is still uncertain. The spatial correlation properties depend on the cloud type and octa[15]. We repeated the analysis of the independent cloud and rain attenuation with varying cloud correlation lengths. In this analysis we modeled the cloud spatial correlation function as an exponential

$$\rho_C(d) = e^{\frac{-d}{D_C}} \quad , \tag{15}$$

where D_C is the correlation length. Increasing the *1/e* correlation length does decrease the availability somewhat, particularly for low link margins where cloud attenuation has a more significant contribution to the overall attenuation. Figure 8 shows an example of link margins of *12.5 dB* and *17 dB* and two different correlation lengths. These results indicate that the cloud effects cannot be neglected.

The impact of clouds is potentially greater than the above analysis indicates. In the absence of any locally measured cloud attenuation statistics we have used the ITU recommended model. Comparison with the limited measured cloud attenuation statistics reported in the literature [8-11] suggests that the ITU model generally underestimates the magnitude of the cloud attenuation.

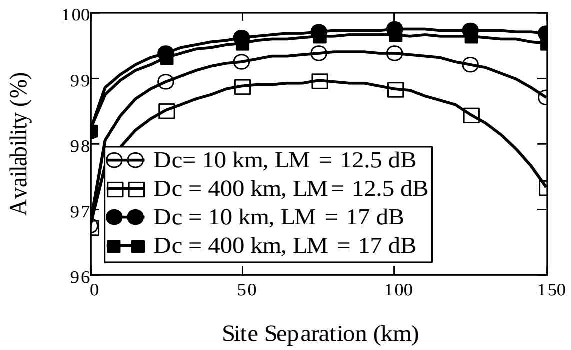

Figure 8. Availability vs site separation for different cloud correlation length and link margins.

5. Conclusion.

It is known that V/W satellite communications will involve substantial atmospheric losses. While rain is the dominant source of attenuation, cloud attenuation cannot be neglected when considering site diversity, particularly with low link margins. The spatial correlation dependence of rain and cloud attenuation has significant impact on the potential utility of site diversity as a fade mitigation technique for V/W systems. This highlights the need for geographically determined parameters as well as improved understanding of cloud attenuation characteristics. Our analysis has shown that it is reasonable to assume that site diversity yielding attractive availability can be attained with the employment of a single high gain satellite antenna illuminating Earth sites with a spacing as close as 50 km. This can minimize the hardware necessary on the payload and greatly simplify the technique for accomplishing site diversity within a satellite architecture. .

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